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# Non-Steady Combustion of Composite Solid Propellants

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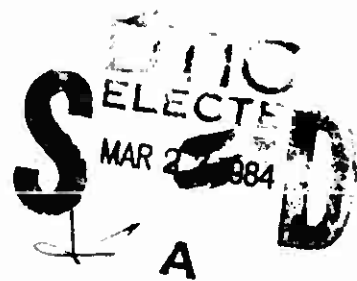
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An analytical model for the linearized velocity-coupled combustion response function was developed. The model combines elements of response to velocity perturbations, pressure perturbations, and compositional perturbations due to the heterogeneity of composite propellants. The important effects of AP size distribution are accounted for in terms of effects on ballistics properties and in terms of periodic fluctuations in propellant composition. Properties of the response function have been calculated theoretically over a range of the

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governing variables. There are two facets of the crossflow problem: the response to velocity perturbations, and the effect of crossflow velocity on the various response elements. The crossflow mechanism is heuristically based upon the so-called "Soderholm erosive burning law," but which has been given physical significance in the theoretical work of Kuo. Significant results are described. In addition, the triggered non-linear instability experiments performed at CARDE were reviewed and shown to depend upon the achievement of a formulation-dependent critical velocity in the rocket motor. Progress was made in the measurement of the pressure-coupled response functions of propellants formulated to seek out the effects of AP particle size. Continued work is needed to perfect experimental methods to characterize effects of composite propellant heterogeneity in terms of compositional fluctuations. Finally, progress was made toward formulating a high frequency combustion response model applicable to nitramine/minimum-smoke propellants.

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iii

## CONTENTS

Figures

# SECTION 1

## RESEARCH OBJECTIVES

### 1.1 OVERALL OBJECTIVE

The objective of this research program is to develop an understanding of oxidizer particle size effects on the non-steady combustion behavior of composite solid propellants. This understanding is expressed by the development of suitable analytical models to describe known or experimentally observed phenomena. A combination of theoretical and experimental tasks is performed toward the accomplishment of this objective. Results are disseminated by technical presentations and publications, and through a variety of interchange functions with government laboratories and contractors. Demands of future propulsion systems and the viability of combustion tailoring through control of oxidizer particle size distribution make it imperative that the effects of size distribution be understood.

### 1.2 SPECIFIC OBJECTIVES FOR FISCAL YEAR 1982

Particular attention has been given to the problem of combustion instability, which is promoted by the development of improved rocket motor capabilities for future missile systems. The specific objectives are listed as follows:

(1) Develop an analytical model for the velocity-coupled combustion response function, accounting for effects of ammonium perchlorate (AP) composite propellant heterogeneity.

(2) Refine and apply experimental techniques utilized during FY 1981 to characterize the composite propellant heterogeneity.

(3) Begin analytical work to characterize the high frequency pressure-coupled response properties of minimum smoke (nitramine/energetic binder) propellants.

A literature survey on analytical response function models which account for effects of AP particle size (i.e., heterogeneity) was completed during FY 1980 (Ref. 1). Following the survey, an analytical model was developed during 1981 for the pressure-coupled response function (Refs. 2, 3). This model accounts for the heterogeneity in two ways: affects of AP particle size on ballistics properties which enter into the response function theory; and compositional fluctuations of frequencies associated with characteristic dimensions of the heterogeneity. The former is in the nature of classical response function theory; the latter incorporates a new mechanism by which the combustion process can drive an instability. Open publication of this work was recently accomplished (Ref. 4). The work planned for FY 1982 consisted of moving on to the subject of the velocity-coupled response. The presence of crossflow and fluctuations in crossflow velocity are important aspects of combustion instability, and more difficult to treat than pressure fluctuations (Ref. 5). Many

believe velocity-coupling to be an essential ingredient of non-linear instability, by which an instability becomes most destructive. As a first step, however, the analytical work would remain in the regime of linear instability. The linearized problem is simpler to treat within the current state of knowledge, and is relevant to the question of stability margin (Ref. 6). It is considered that much can be learned from the properties of the linear velocity-coupled response. It is planned to begin work on the non-linear response in 1983.

Three types of experiments have been explored to characterize the heterogeneity of composite propellants and its effects on combustion behavior. The first experiment, which is non-destructive, is to perform energy dispersive analysis of x-rays (EDAX) scans of propellant samples, and Fourier decompositions of the measured fluctuations in chlorine intensities representative of local AP concentrations. The second experiment is to use the JPL microwave burner (Ref. 7) to measure dynamic burning rates of the same propellants at constant pressure, and to analyze the data for frequency components. The third experiment is to use the burner to measure pressure-coupled response functions of these propellants and determine peak response frequencies. It is desired to seek the consistent appearance of any preferred frequencies, and to relate the observed frequencies to the heterogeneity of real propellants. Feasibility of the approach was established in FY 1981 work (Refs. 2, 8), but technique refinements are needed to extract the preferred frequencies, and more experiments are needed to establish their consistency. Plans for FY 1982 included continuation of this experimental work.

Minimum smoke propellants have exhibited a propensity toward high frequency tangential mode instability (Ref. 9). The high frequency regime introduces the question of gas phase time lag as an important contributing mechanism, and therefore the need to relax the quasi-steady gas assumption commonly used in response function theories. One work, by Tien, has relaxed this assumption (Ref. 10), but the results are suspect because of the prediction of a negative response over a broad frequency range that is contrary to experience. Another interesting aspect of minimum smoke propellants is that their combustion behavior exhibits the characteristics of homogeneous propellants (Ref. 11). Therefore, an approach that neglects heterogeneity but relaxes the quasi-steady gas assumption appears viable. It was planned to review the basis of Tien's work with intentions to revise that work as necessary and study the resulting properties. The pressure-coupled response properties of minimum smoke propellants are important because high frequency stability additives may be precluded or ineffective (Ref. 9).

# SECTION 2

# STATUS OF THE RESEARCH EFFORT

## 2.1 VELOCITY-COUPLED RESPONSE MODELING

### 2.1.1 Analysis of the Linear Velocity-Coupled Response Function

A theoretical analysis of the linear velocity-coupled response function has been completed. This work complements the previous analytical developments for the pressure-coupled response function, including a compositional response mechanism to account for composite propellant heterogeneity (Refs. 2-4). There are two aspects of the problem of linear velocity-coupling. First, as pointed out by Lengelle (Ref. 12), is the effect of mean crossflow velocity on the various response function parameters. Second is the combustion response to fluctuations in the velocity, which is the velocity-coupled response function. Both aspects are of interest in this study.

The basic mechanisms are time lags in the solid phase driven by pressure and velocity perturbations in the gas phase. Added to these perturbations are compositional fluctuations which originate in the solid phase; this is the effect of heterogeneity. The analysis is limited to conditions under which quasi-steady gas assumptions and principles of linearization apply.

The effect of crossflow velocity basically involves a boundary layer heat transfer mechanism, by which the static heat feedback from the combustion zone is modified and augmented. Under steady-state conditions, the phenomenon is commonly referred to as "erosive burning." Where the flow has an oscillating component, as during unstable burning, the combustion response to this oscillating component is sometimes referred to as the "erosive response," but is more often called the "velocity-coupled response." Velocity-coupling itself may involve more than combustion response (Ref. 5), but this research is limited to the question of combustion response. A number of theoretical analyses describing the boundary layer heat transfer mechanism in the context of solid propellant combustion have been published in recent years (Refs. 12-21). There is much disagreement in describing the mechanism, and the problem has not been resolved.

The approach adopted in this work has been to consider the boundary layer interaction mechanism as a separate problem, and concentrate on the combustion response to whatever the perturbing function is that is transmitted. The boundary layer interaction mechanism is a subject of continuing work by others (Refs. 22, 23) and, when sufficient progress is achieved, the intention is to combine the elements into a fully coupled model that would ultimately entail nonlinear effects (Refs. 24, 25) and probably the core gas dynamics (Ref. 26) as well.

In view of the above-mentioned uncertainty, and the desire to concentrate on the combustion response (with emphasis on AP particle size effects), it was assumed that influences of crossflow velocity could be represented by an addition to the surface energy balance taking the form of Saderholms' law (Ref.

2-1

27). This particular law was selected because it has a good history of corre-
lating erosive burning data over a wide range of conditions (Refs. 28, 29),
appears to have the proper interplay between controlling variables that any
mechanistic-based theory would have to match, and has been given mechanistic
support in the work of Kuo, et al. (Ref. 30). The Saderholm expression would
be of the form

$$E = K_1 \left(u_0/u_t\right)^{N_u} (P_0)^{N_p} \tag{1}$$

Assuming the erosive threshold, $u_t$, to increase with increasing burning rate
and decreasing particle size (Ref. 14), Eq. (1) becomes the additive energy
transport term

$$E = K_2 \left(u_0\right)^{N_u} (P_0)^{N_p} (D_0)^{N_D} / (r_0)^{N_r} \tag{2}$$

This equation was optimized to fit the Cohen-Strand model of steady-state burn-
ing (Ref. 31) to all of the experimental data of King (Ref. 18). The resulting
standard deviation between calculated and experimental burning rates, r, when
compared as

$$\frac{\left| \left(\frac{r}{r_0}\right)_{calc} - \left(\frac{r}{r_0}\right)_{exp} \right|}{\left(\frac{r}{r_0}\right)_{exp} - 1} \times 100$$

was 24%. This is considered quite good when compared on this basis (Ref. 32),
because it is comparing the incremental burning rates rather than the burning
rates themselves. Also, it better reflects the error between the calculated E
and that value of E required in the model to match the experimental result
exactly.

It should be restated that the significance of E in this approach is as
part of a boundary condition, to represent a transport mechanism that has not
yet been conclusively quantified in independent theoretical analysis. As such,
its semi-empirical origin does not render the approach unscientific or without
physical significance. For example, it is of interest that the value of the
particle size – dependence, $N_D$, is a number close to zero ($N_D = 0.15$). This
means that the effect of a coarse particle is largely due to the fact that the
blowing ($r_0$) tends to be low, and not due to the fact that there is a big
particle sticking up into the boundary layer. Also, the value of the velocity-
dependence, $N_u$, is a number close to 0.8 ($N_u = 0.87$). Such a dependence is
mindful of classical convective-heating.

With E thus established and added to the model, a perturbation analysis
provides the velocity-coupled response. The three response function elements
which have been derived in the course of this work may be expressed as:

2-2

$$R_p/n_p = 1/L \tag{3}$$

$$R_a/n_a = [1 - (K_\rho/n_a)\, \sigma_p\, (T_{w_0} - T_0)\, (1 - 1/\lambda)]/L \tag{4}$$

$$R_u/n_u = (a_0/u_0)/L \tag{5}$$

where

$$L = 1 - \sigma_p\, (T_{w_0} - T_0)\, (1 - 1/\lambda) + \sigma_T\, (\lambda - 1) \tag{6}$$

$$\sigma_p = \left(\frac{\partial \ln m}{\partial T_0}\right)_{P,\,a,\,u} \tag{7}$$

$$\sigma_T = \left(\frac{\partial T_w}{\partial T_0}\right)_{P,\,a,\,u} \tag{8}$$

$$n_p = \left(\frac{\partial \ln m}{\partial \ln P}\right)_{a,\,u,\,T_0} \tag{9}$$

$$n_a = \left(\frac{\partial \ln m}{\partial \ln a}\right)_{P,\,u,\,T_0} \tag{10}$$

$$n_u = \left(\frac{\partial \ln m}{\partial \ln u}\right)_{P,\,a,\,T_0} \tag{11}$$

The real parts of Eqs. (3) and (4) combine to achieve the overall driving pressure-coupled response; the imaginary parts of Eqs. (4) and (5) combine to achieve the overall driving velocity-coupled response.

## 2.1.2 Parametric Studies

Series of computations were performed over ranges of the controlling combustion parameters, as reported previously (Refs. 2-4), but now the mean flow velocity is added as a parameter and the velocity-coupled response parameters are added as calculated dependent variables. Calculations were made at velocities of 200, 400 and 600 m/sec. Results at 0 m/sec, where the velocity-coupled response would be 0 ($u_t > 0$), were reported previously. The review of the results may be highlighted as follows.

2-3

With respect to the influence of mean flow velocity on the controlling ballistics properties, increasing $u_0$ tends to

- increase burning rate, $r_0$

- increase pressure exponent, $n_p$

- reduce burn rate-temperature sensitivity, $\sigma_p$

- increase surface temperature, $(T_w - T_0)_0$

- decrease surface temperature-temperature sensitivity, $\sigma_T$, or cause it to go through a minimum at an intermediate velocity

- decrease concentration exponent, $n_\alpha$

- decrease velocity exponent, $n_u$

With respect to the influence of mean flow velocity on the pressure-coupled response function elements, increasing $u_0$ tends to

- change the peak value of $R_p$ in a non-systematic way, but the changes are generally small: the larger peak values at $u_0 = 0$ tend to decrease with increasing $u_0$, and this change is more substantial

- decrease the peak value of $R_\alpha$, the largest decreases occurring for the largest peak values at $u_0 = 0$

- increase peak response frequencies, generally due to the increase in $r_u^2$, but sometimes there also is a step-up in the peak dimensionless frequency $\Omega$; usually the peak-response $\Omega$ decreases very slightly with increasing $u_0$.

These results are, of course, colored by the particular combustion model that is used, but they do appear reasonable. Combining the pressure-coupled response elements, increasing the crossflow velocity will tend to be stabilizing at lower frequencies (near and below the peak response frequencies at $u_0 = 0$), and to shift the response function curve to higher frequencies, where it will eventually be destabilizing. Effects of AP particle size are as reported previously (Refs. 2-4).

Results for the properties of the velocity-coupled response are fascinating. First, the typical appearance of a velocity response function curve is displayed in Figure 1. The imaginary part of the velocity-coupled response is the component that is pertinent to the combustion instability driving. There are two regions of interest: at low frequency, burn rate fluctuations are phase-leading and the imaginary part is positive; at high frequency, burn rate fluctuations are phase-lagging and the imaginary part is negative. This distinction is very important to the grain design of a rocket motor because it determines whether velocity-coupling adds or subtracts acoustic energy at particular locations (Refs. 33, 34). Three key frequencies are noted on the plot:
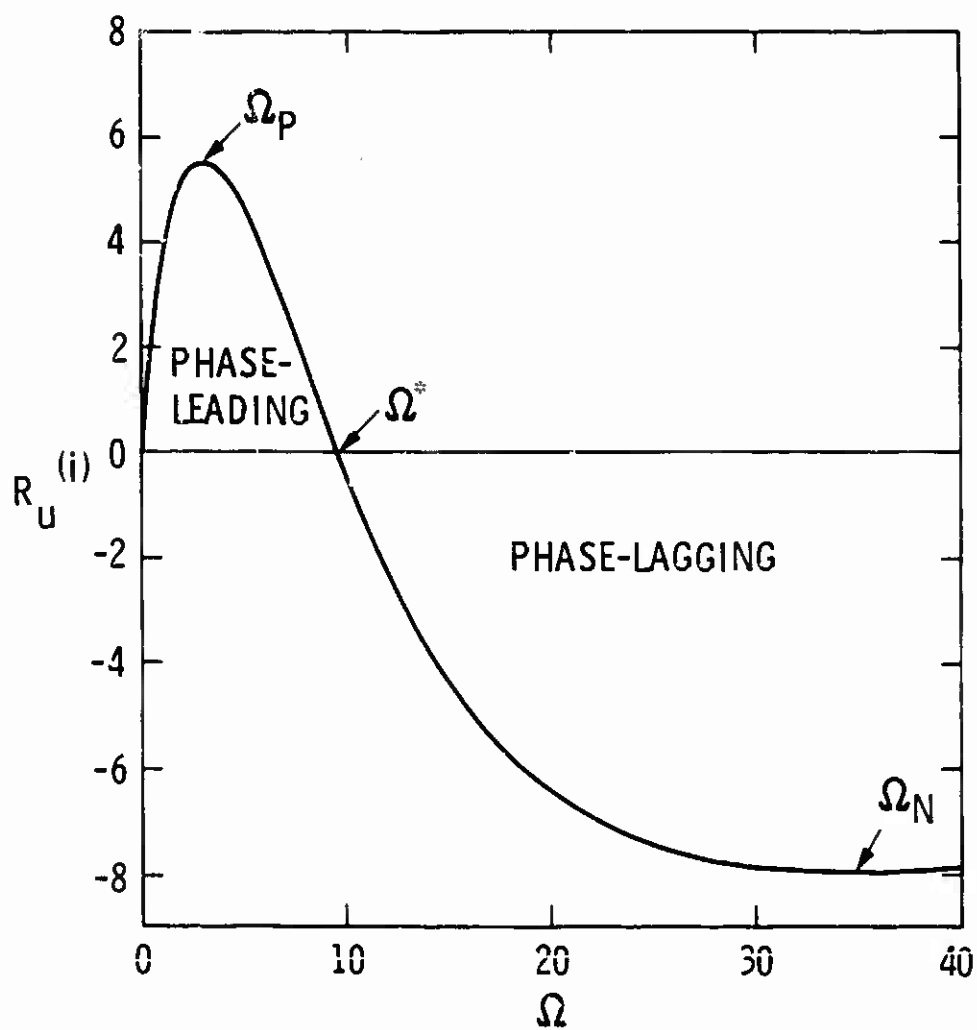
Figure 1.  Velocity Response Function Curve Typified by Calculations
for the Case 73% AP, 200 μm Particle Size, 68 MPa Pressure
and 200 m/sec Mean Crossflow Velocity

that corresponding to the positive peak response $(\Omega_p)$, that corresponding to the negative peak response $(\Omega_N)$, and that corresponding to the sign change $(\Omega^*)$. It is a typical result that the negative values reach somewhat larger absolute magnitudes than the positive values, and that the negative part exhibits a relatively broad and flat peak region compared to the positive part.

The imaginary part of the compositional response, $R_a^{(i)}$, exhibits qualitatively similar features and properties as the imaginary part of the velocity response. This was also true in comparing the real parts of the compositional and pressure responses, as reported previously (Refs. 2-4). However, whereas the compositional response always achieved magnitudes far larger than the pressure response, such that it could be inferred that the heterogeneity would dominate pressure-coupled driving, the magnitudes of the compositional and velocity responses are more comparable. The magnitudes of the compositional response tend to exceed the velocity response at lower AP concentrations, lower pressures, and with finer AP particle sizes. The magnitudes of the velocity response tend to exceed the compositional response at higher AP concentrations, higher pressures and with coarser AP particle sizes. Therefore, with regard to velocity-coupling, the heterogeneity is important, though not as dominating an influence as with pressure-coupling.

Another consequence of relatively large values of both the compositional and velocity responses is that the velocity-coupled response can tend to have larger values than the pressure-coupled response. Experimental measurements or deductions of absolute values in excess of 10 have been frequent and often viewed with suspicion. This work supports such large values, and does so with confidence because theoretical and experimental values of the exponents (for pressure, $n_p$, for composition, $n_a$, and for velocity, $n_u$) are in fairly good agreement and because values of $n_u$ are generally much larger than values of $n_p$.

Qualitative effects of the temperature-sensitivity parameters, $\sigma_p$ and $\sigma_T$, upon the velocity response are the same as upon the pressure response. Increasing $\sigma_p$ tends to increase the peak values and narrow or sharpen the peak regions. Increasing $\sigma_T$ tends to decrease the peak values and narrow the peak regions. The response is proportional to the exponent. Effects of AP particle size upon $n_u$ are not systematic, but $n_u$ generally tends to increase with increasing AP content, increasing pressure and decreasing velocity.

Figure 2 shows the effects of AP particle size and pressure upon the phase-leading peak values of the imaginary part of the velocity response. These calculations were made for 88% AP and a mean flow velocity of 200 m/sec, but the results typify the qualitative behavior. The most striking feature is the sharp increase with pressure in the coarse AP regime, and the very large peak values attainable. In general, the peak response values increase with pressure and particle size although an intermediate maximum appears at an intermediate particle size. Figure 3 shows the effects of AP particle size and crossflow velocity at constant pressure. The striking feature here is the sharp increase with decreasing velocity in the coarse AP regime. In general, the peak response values increase with decreasing velocity over the range of velocities considered. Effects upon the phase lagging peak, and upon the analogous peaks for $R_a^{(i)}$ are qualitatively the same. More calculations with further decreases in crossflow velocity would be of interest.
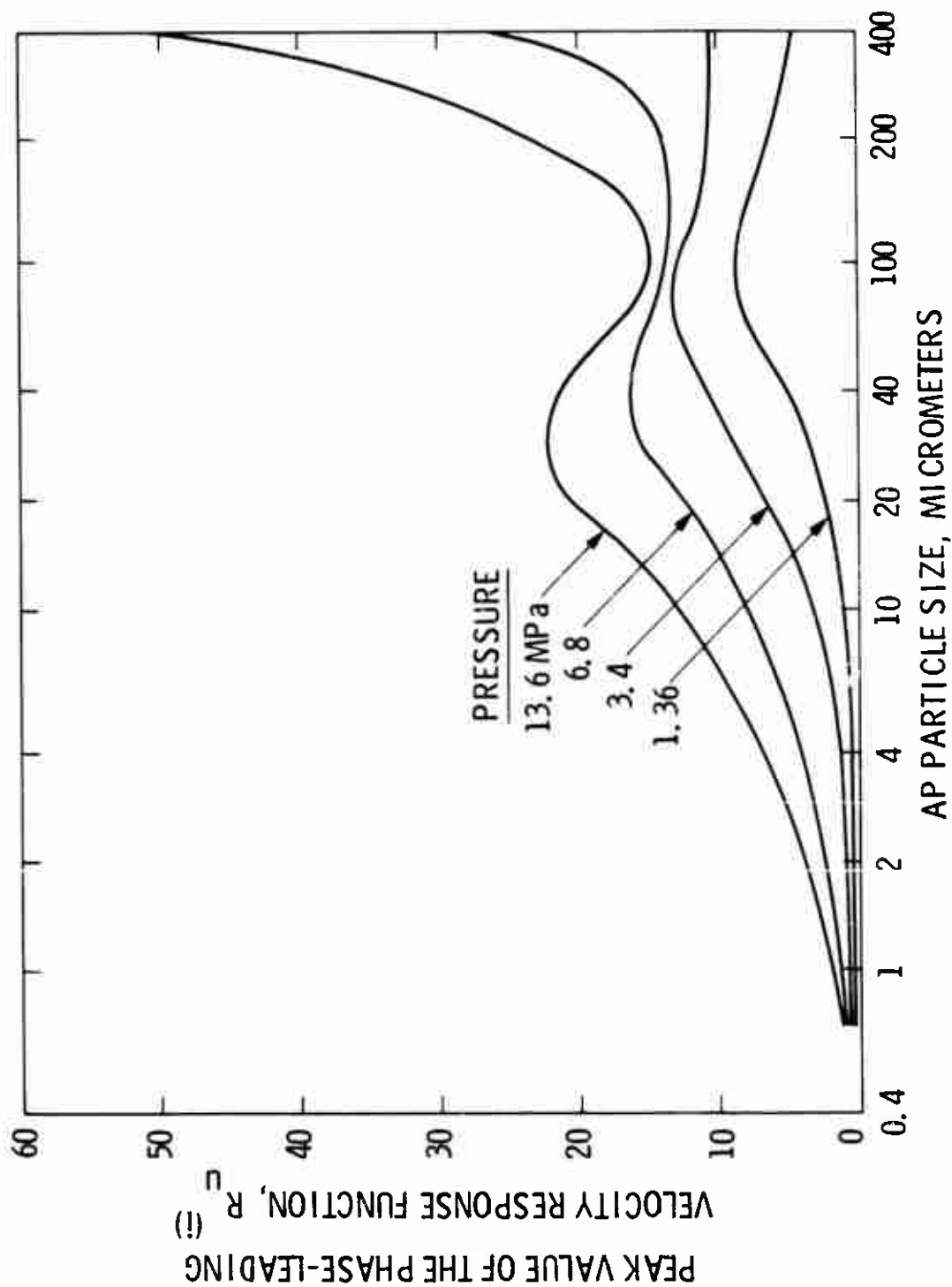
Figure 2. Effects of AP Particle Size and Pressure on a Peak Value of the Velocity Response, 88% AP and 200 m/sec Mean Crossflow Velocity
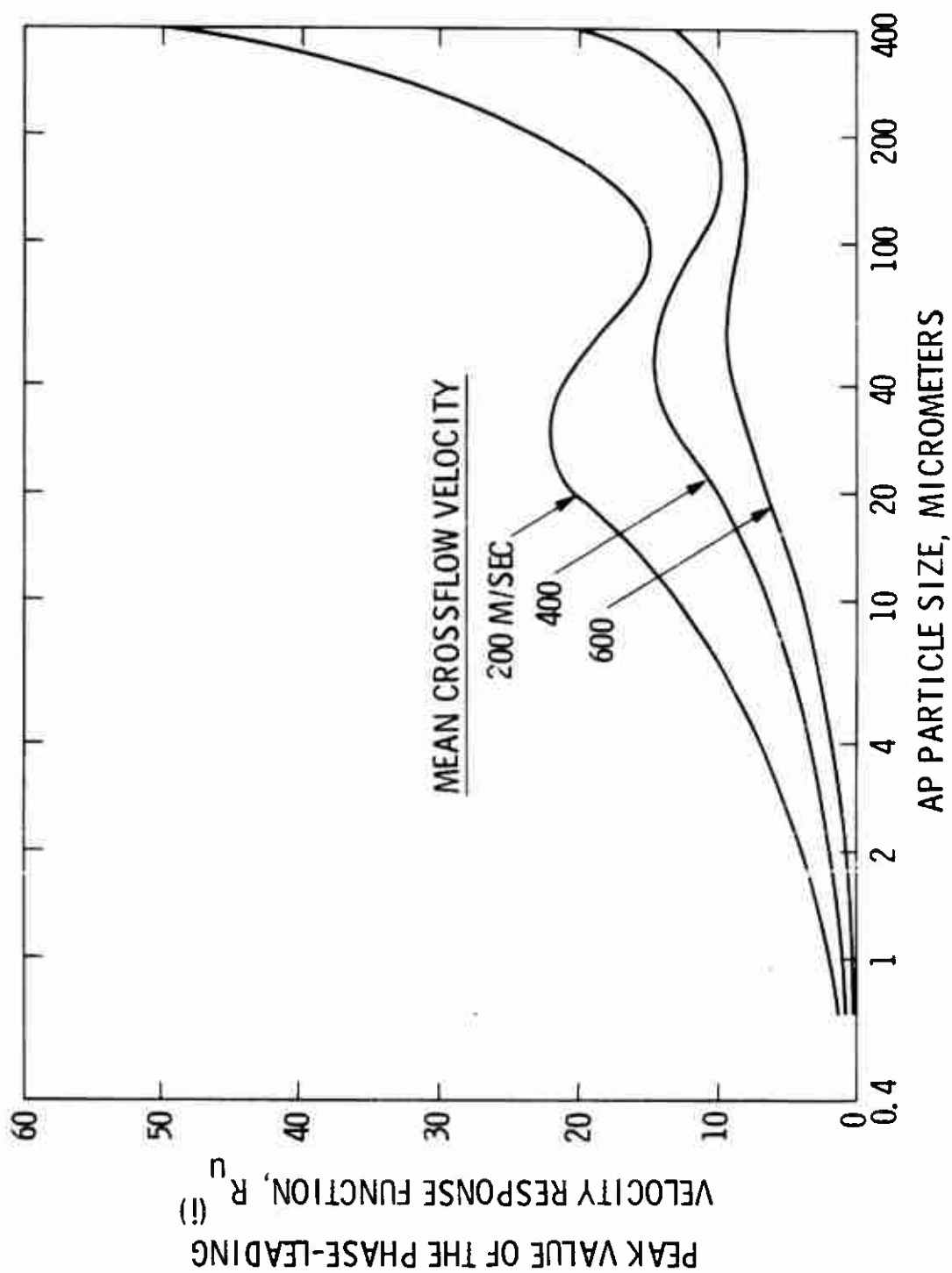
Figure 3. Effects of AP Particle Size and Mean Crossflow Velocity on a Peak Value of the Velocity Response, 88% AP and 13.6 MPa Pressure

The three key frequencies tend to increase with variables which bring about an increase in burning rate: increased pressure, velocity and AP content, and decreased particle size. An interesting result is a step-up in the values of $\Omega$ that sometimes occurs in the course of each of these variations in the independent variables. Combined with the normal burn rate increase, this step-up in the $\Omega$ causes a relatively large and sudden shift in the frequencies. The reason for this behavior is not clear, and merits further study because the frequency separating phase lead and phase lag response, in particular, is of special importance and whatever causes it to change sharply would be of interest.

Perhaps the most important highlight is that the velocity-coupled response is largest at combinations of coarse AP/low burn rate, high pressure and low mean flow velocity (but in excess of threshold velocity). This is very gratifying because it is entirely consistent with experience. Figures 2 and 3 would suggest that 400 $\mu$m AP be avoided, especially due to the fact that this material varies from lot-to-lot and often contains tails of very coarse particles in the size distribution. Other figures of this type could be generated to furnish developmental guidelines, but it is cautioned that specific results are subject to uncertainties in the combustion model and that the heterogeneities of propellants must be determined before this theoretical work can be properly applied. Nevertheless, there is much food for thought and future work could profit from delving further into the reasons for the calculated trends.

2.1.3 Pulse-Triggered Nonlinear Instability: Review of CARDE Experiments

A classical series of experiments was carried out by Brownlee (Ref. 35) in which the ability to trigger axial mode, nonlinear instability by pulse-injection in tubular-grain rocket motors was mapped as a function of pressure and geometric variables. He correlated the data in terms of a critical pressure-$K_n$ relationship, and mapped a stability boundary as $K_n$ versus port diameter. These relationships were found to be dependent upon propellant formulation in a given motor, and upon the type of motor (Refs. 35-37). Significantly, slower burning-rate propellants were always more susceptible to this type of triggering in the experiments conducted. In view of the generally-held belief that velocity-coupling is responsible for this type of instability (Ref. 5), a review of the work was deemed appropriate as part of the evolution of this research into the area of nonlinear velocity-coupling.

An important characteristic of the Brownlee experiments is that it was conducted by reducing the nozzle throat area on successive motors. This served to increase the ranges of $K_n$ and pressure encountered from motor to motor, using a progressive-burning tubular grain. Below a certain pressure/$K_n$, the instability could not be triggered. Above that pressure/$K_n$, the triggered instability progressively increased in severity with increasing pressure/$K_n$. By reducing the throat size from motor to motor, the instability could be triggered earlier in the firing and stronger instability could be excited later in the firing.

The Brownlee data were examined to see if the triggering could be associated with the achievement of some critical low axial velocity in the port. It was noticed that the results might also be interpreted on the basis of a

critical J, because the smaller the throat the smaller the port at which triggering could occur. Sufficient information was provided to enable calculations of the port exit velocity corresponding to each triggering boundary point. For ports ranging from 2.64-3.77 cm. diameter, $K_n$ varying between 237 and 332, and pressures ranging from 2.46-3.84 MPa, at triggering, the exit velocities were computed to vary from 111-116 m/sec. This near-constant value is considered to be significant, although the significance at this time can only be speculated. It might be an indication of the erosive threshold velocity. It might be related to the pulse strength in terms of the ability of the compression wave reflection to stop or reverse the flow, or cause the flow to fall below the erosive threshold. In any event, this observation should be noted for future work.

Later experiments (Refs. 36, 37) were not so extensive as to permit the evaluation of the consistency of the critical velocity for a given propellant and motor, but a value for the critical velocity could be determined. Results for five propellants are tabulated below, relating the port exit velocity to the propellant burn rate at the triggering boundary point.

| Burn Rate (cm/sec) | Port Exit Velocity (m/sec) |
|---|---|
| 0.31 | 91 |
| 0.40 | 114 |
| 0.63 | 202 |
| 0.70 | 193 |
| 0.82 | 216 |

With one exception, there is a good relationship between the burn rate and the velocity, the velocity decreasing with decreasing burn rate. Whether this tabulation is some indication of the relationship between erosive threshold and burn rate is speculation, but ought to be kept in mind.

On the basis of this revised interpretation of the CARDE work, it would be concluded that triggering is made more difficult not so much by lowering the operating pressure, but rather by maintaining an adequate port flow velocity during burn. This adequate velocity may be preventing flow reversals or a fall below erosive thresholds.

## 2.2    EXPERIMENTS TO CHARACTERIZE HETEROGENEITY EFFECTS

### 2.2.1  Propellants

In attempting to characterize the heterogeneity of solid propellants, three propellants were especially formulated to highlight particle size effects. Each contained 25% HTPB binder and 75% AP oxidizer. The oxidizer size fractions were sieved to narrow each distribution. One propellant contained a monomodal fine (45 $\mu$m) oxidizer size, one a monomodal coarse (180-212 $\mu$m) size, and one had a 50/50 bimodal blend of the two.

### 2.2.2  Microwave Burner Tests

Dynamic burning rate data with improved signal-to-noise characteristics were obtained for the three propellants at a single pressure of 3.5 MPa (500 Psi). The reduced noise was obtained by cutting down on the electrical noise superimposed on the recorded microwave phase-shift test signal. The recorded data will be Fourier-analyzed to determine their frequency spectral density.

Pressure-coupled response function data (at the same burning pressure) were obtained for the three propellants at narrow frequency intervals over the range 40-1500 Hz. The dynamic burning rate frequency spectra will be compared to the combustion response function vs. frequency characteristics to see if some dominant frequency or frequencies appear in the combustion response. Microwave response function data for several other propellants, obtained under an AFRPL-sponsored program, are also available to supplement this research.

A few additional dynamic burning rate and response function measurement tests will be made at varying mean burning rates (varying mean pressure) to verify consistency (higher mean burn rate should evoke higher frequencies).

### 2.2.3  EDAX/SEM Studies

This year's effort concentrated on the microwave dynamic burning rate and response function measurements, and limited work was done with the EDAX/SEM experimental approach for characterizing the heterogeneity of actual composite propellants, mainly in the area of improvement of sample preparation techniques. The feasibility of this approach was demonstrated last year from tests carried out on the composite propellant formulation A-13. It was concluded that the propellant formulation did fluctuate on the macroscopic scale and these fluctuations had significant amplitudes and considerable frequency content.

In the future EDAX photographs will be taken of the three specially for-mulated propellants, varying magnification, sample location, and sample orien-tation. Frequency distributions derived from Fourier analysis of the composi-tional fluctuations will be studied for ordering and for relationships to char-acteristic dimensions of the fine structure. A statistical analysis of the results will be carried out to determine the validity and consistency of the appearance of preferred frequencies. The relationships between any dominant fre-quencies in the propellant heterogeneity and dynamic burning rate data and the measured response function - frequency characteristics will be determined.

## 2.3    HIGH FREQUENCY COMBUSTION RESPONSE MODELING

### 2.3.1  Limits of the Quasi-Steady Gas Assumption

The upper frequency limit to the validity of the quasi-steady gas assumption is a subject of some confusion.  Numbers are often stated, but these numbers are at such variance that their factual bases are suspect.  Therefore, as a first step in this work, it was deemed necessary to verify the upper frequency limit, and with specific reference to the nitramine/minimum-smoke propellant family that is of interest.

The quasi-steady gas assumption is valid if both of the following conditions are satisfied (Ref. 1C).  First, the residence time of the gas in the flame must be small compared to the characteristic thermal time of the solid phase.  Second, the residence time of the gas in the flame must be small compared to the period of oscillations.

The first condition may be expressed as the ratio

$$b_1 = \frac{r \ X^* \ c_g^2 \ p}{k_s \ c_s \ RT_F} \tag{12}$$

Assuming that $r$ varies with the 0.7 power of pressure and with the propellant heat of explosion (Ref. 38), that $X^*$ may be determined from a first-order Arrhenius kinetics law, and that $c_s = c_g$, Eo. (12) may be rewritten as

$$b_1 = \frac{r_{REF} \ X^*_{REF} \ P_{REF} \ c_s}{RT_{F_{REF}} \ k_s} \left(\frac{p}{P_{REF}}\right)^{0.7} \left(\frac{T_F}{T_{F_{REF}}}\right) \exp\left[\frac{E_g}{R}\left(\frac{1}{T_F} - \frac{1}{T_{F_{REF}}}\right)\right] \tag{13}$$

where the subscript REF denotes a reference condition, namely a propellant of average energy level burning at 6.8 MPa.  Using values for the combustion constants that are used in current theories of burning of energetic binder propellants (Ref. 39), a reference flame height calculated from the theory, and taking the flame temperature to be that of the primary or fizz zone (which is much lower than that of the final flame) (Ref. 38), $b_1$ may be calculated to have the following extreme values:

high energy propellant at a boost pressure, $o_1 = 0.022$
reference condition, $b_1 = 0.015$
low energy propellant at a sustain pressure, $b_1 = 0.011$

Therefore, the first condition is always satisfied.  The second condition may be expressed as the ratio

$$h_2 = \frac{X^* \, Pf}{\rho_p \, r \, RT_F} \tag{14}$$

which may similarly he rewritten as

$$b_2 = \frac{X^*_{REF} \, P_{REF} \, f}{\rho r_{REF} \, RT_{REF}} \quad \frac{\exp\left[\frac{Eg}{R}\left(\frac{1}{T_F} - \frac{1}{T_{F_{REF}}}\right)\right]}{\left(\frac{T_F}{T_{F_{REF}}}\right)^3 \left(\frac{P}{P_{REF}}\right)^{0.7}} \tag{15}$$

For the specification that $h_2$ cannot exceed 0.1, the following upper-limit frequencies are calculated

high energy propellant at a hoost pressure. f = 16000 Hz
reference condition, f = 5100 Hz
low energy propellant at a sustain pressure, f = 900 Hz.

Thus the guasi-steady gas assumption has a broader range of applicability than is often stated, and in many cases covers the high freguencies enccuntered in motors. Limiting the assumption to 1000 Hz is an understatement. particularly since the phenomenon is of greater interest with higher energy propellants and at higher pressures.

## 2.3.2 Applicability of the Classical Theory at Acceptable Frequencies

With this guestion settled, the classical theory of Denison and Baum (Ref. 40) was examined to see if the numerics would be viable for nitramine/minimum smoke propellants. It was shown that they are not for AP-composite, or reduced smoke, propellants (Ref. 1). These two classes of propellants differ in the values of their essential combustion constants. Calculations of the so-called "A and B parameters" in this model were made. The range of values of A (15-20) and B (0.6-1) are such as to generate satisfactory response function curves wih strong peaks and reasonahle high freguency responses, rather than flat-looking curves with weak responses. Therefore, it is considered that this theory is worthy of further use in studying minimum smoke propellants up to the freguencies indicated ahove. This was left for future work.

## 2.3.3 Reformulation of the Tien Theory

There may be difficulties in Tien's work in that solution of the coupled second-order differential equations is not a simple matter and often incurs numerical convergence prohlems. Another aspect of the problem that could bear strongly upon the types of solutions obtained is his statement of the boundary condition at the flame. In this regard Tien used a single flame, whereas it is known that the combustion of minimum smoke propellants in the gas phase is at least two-staged (Refs. 41-44). Therefore, the approach that was taken was to see how the eguations could be simplified to avoid potential numerical problems. examine and perhaps modify the boundary condition at the flame, and incorporate a two-stage flame model. The work would serve to cover frequencies in excess of those permitted by the quasi-steady gas assumption, and strive to achieve more reasonable results.

Progress consisted of setting down the conservation equations for the condensed phase, the primary flame zone and the final flame zone in the gas phase. The fizz zone was simplified, relative to what Tien did, by assuming a constant reaction rate that not only simplifies the energy equation but also eliminates the need for the species equations. This assumption has been justified by the low activation energy of the primary zone kinetics (Ref. 41). The final flame zone is treated in a simplified manner by assuming that a flame sheet model applies. This assumption has been justified by the high activation energy of the final flame kinetics. As a result, the species equations are again not needed and the energy equation is again simplified. It is considered that the essence of the problem is still retained.

Discussions concerning the boundary conditions at the flames were initiated with Dr. Fred Culick at the California Institute of Technology. This aspect of the work was not completed. Dr. Culick expressed interest in this work and would be willing to contribute if it is resumed in the future.

Further work on this task was delayed in favor of the velocity-coupled response function modeling work. This resulted from a program reduction, the projected ability to arrive at a certain level of completion of the velocity-coupling work within the known available funding, and an awareness that Flandro (Ref. 24) was including the high frequency regime in his own theoretical work under Air Force sponsorship. Depending upon priorities, and the nature of Flandro's progress, it would be proposed to resume this work in the future.

# SECTION 3

## TECHNICAL PUBLICATIONS

The following publications appeared in the AIAA Journal during the past year:

(1) Strand, L. D., and Cohen, N. S., "Porous Plate Analog Burner Study of Composite Solid Propellant Flame Structure," AIAA Journal, Vol. 20, No. 4, April 1982, pp. 569-570.

(2) Cohen, N. S., and Strand, L. D., "An Improved Model for the Combustion of AP Composite Propellents," AIAA Journal, Vol. 20, No. 12, Dec. 1982, pp. 1739-1746.

The following revised paper has been accepted for AIAA Journal publication, and publication is pending:

(3) Cohen, N. S., "A Pocket Model for Aluminum Agglomeration in Composite Propellants," presented originally as AIAA Paper 81-1585.

The following paper appeared in a Chemical Propulsion Information Agency (CPIA) publication during the past fiscal year:

(4) Cohen, N. S., and Strand, L. D., "Effects of AP Size Distribution on the Pressure-Coupled Response Function," 18th JANNAF Combustion Meeting, CPIA Publication 347, Vol. III, Oct. 1981, pp. 7-20.

# SECTION 4

## PROFESSIONAL PERSONNEL

The Principal Investigator for this program is Leon D. Strand of the Thermochemical Research and Systems Section (M/S 125-159), Jet Propulsion Laboratory/California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109 (telephone 213-354-5108). His co-investigator is Dr. Norman S. Cohen, Cohen Professional Services, 141 Channing St., Redlands, California 92373 (telephone 714-792-8807).

Mr. Strand has overall program responsibility and specific responsibility for the experimental work performed. Dr. Cohen works under a subcontract, and is responsible for the analytical model developments. Both are former members of the AIAA Technical Committe on Propellants and Combustion. Mr. Strand is currently an associate editor of the "AIAA Journal of Spacecraft and Rockets," and Dr. Cohen is a member of the JANNAF Combustion Working Group.

# SECTION 5

## INTERACTIONS (COUPLING ACTIVITIES)

### 5.1    PRESENTATIONS

The following presentations were made under this research contract:

(1)    Cohen, N. S., and Strand, L. D., "Non-Steady Combustion of
Composite Propellants," 1982 Joint AFOSR/AFRPL Rocket Propulsion
Research Meeting, Lancaster, California, March 1982.

(2)    Cohen, N. S., and Strand, L. D., "Combustion Response to
Compositional Fluctuations," AIAA Paper 83-0476, 21st AIAA
Aerospace Sciences Meeting, Reno, Nev., Jan. 1983.

### 5.2    INTERCHANGE FUNCTIONS WITH GOVERNMENT LABORATORIES AND CONTRACTORS

Information derived from past research on the subject of nitramine
propellant combustion was used to complement current efforts in progress at
Thiokol Corporation (Dr. D. A. Flanigan, Huntsville Div.) under Air Force
sponsorship and at Lockheed Missiles and Space Co. (Dr. G. A. Lo, Palo Alto
Research Laboratory).  The analytical model describing the steady-state burning
of solid propellants in general, developed in the course of prior research, is
being used to assist the development of low $\pi_k$ (temperature sensitivity) pro-
pellants at Thiokol Corporation (Dr. D. A. Flanigan, Huntsville Div.) under Air
Force sponsorship.  This model also has been used in the course of informal
contacts with other model developers (J. P. Renie, Purdue University, Dr. M.
W. Beckstead, Brigham Young University, M. K. King, Atlantic Research Corpora-
tion) to compare certain model calculations.  Several useful discussions were
held with Dr. Beckstead regarding the thermochemical bases for the energetic
binder combustion model developed by him under Air Force sponsorship.

Productive interchanges have also taken place regarding the subjects of
the current research effort.  R. R.  Miller (Hercules Inc.. ABL Div.) has
observed and measured dynamic burning at constant pressure by microcinematogra-
phy of propellant strands containing coarse AP.  Additional evidence of multi-
peaked response function curves has been acquired at this laboratory and at the
Georgia Institute of Technology (Dr. B. T. Zinn) in related work under Air
Force sponsorship.  The effect of AP size distribution on combustion response
has also been the subject of communications with Thiokol Corporation
(R. O. Hessler and J. O. Hightower, Huntsville Div., and D. P. Clark, Wasatch
Div.), Purdue Unversity (Dr. R. L. Glick, Prof. J. R. Osborn and J. P. Renie),
Aerojet Tactical Systems (M. J. Oitore) and United Technologies Corp.  (Dr.
T. P. Rudy, Chemical Systems Div.); two of these involved practical motor
development programs.  The EOAX and microwave burner techniques may find useful
application in the quality control evaluation of Space Shuttle SRM propellant
batches as a result of discussions with Thiokol Corporation (L. H. Sayer,
Wasatch Div.) and NASA (Dr. B. Shackelford, Mashall Space Flight Center).  With
respect to velocity-coupled instability, the reported work at the Princeton
Combustion Research Laboratory (Dr. M. Ben Reuven) has been reviewed and

commented upon, information generated by M. K. King (Atlantic Research Corpora-
tion) and K. Kuo (Pennsylvania State University) under Air Force sponsorship
has been used in this program, and frequent discussions have been held with
J. N. Levine (Air Force Rocket Propulsion Laboratory, AFRPL) regarding progress
under this and related AFRPL-sponsored programs. It is planned to take an
active role in defining the integration of the various velocity-coupling ele-
ments being worked upon in the course of future work.

# REFERENCES

1. Cohen, N. S., "Response Function Theories That Account for Size Distribution Effects - A Review," AIAA Journal, Vol. 19, No. 7, July 1981, pp. 907-912.

2. Cohen, N. S. and Strand, L. O., "Non-Steady Combustion of Composite Solid Propellants," Annual Research Progress Report under AFOSR-ISSA-81-0019, Jet Propulsion Laboratory/California Institute of Technology, Pasadena, Calif., April 1982.

3. Cohen, N. S. and Strand, L. D., "Analytical Model of Contributions of Composite Propellant Heterogeneity to the Combustion Response Function," supplemental dissertation prepared and submitted under AFOSR-ISSA-81-0019, Jet Propulsion Laboratory/California Institute of Technology, Pasadena, Calif., March 1982.

4. Cohen, N. S. and Strand, L. D., "Combustion Response to Compositional Fluctuations," AIAA Paper 83-0476, 21st AIAA Aerospace Sciences Meeting, Jan. 1983.

5. Beckstead, M. W., "Workshop Report on Velocity Coupling," 17th JANNAF Combustion meeting, CPIA Publication 329, Vol. I, Nov. 1980, pp. 195-200.

6. Lovine, R. L., Waugh, R. C. and Oudley, D. P., "Standardized Stability Prediction Method for Solid Rocket Motors," AFRPL-TR-76-32, Aerojet Solid Propulsion Company, Sacramento, Calif., May 1976.

7. Strand, L. D., Magiawala, K. R. and McNamara, R. P., "Microwave Measurement of the Solid Propellant Pressure-Coupled Response Function," J. Spacecraft and Rockets, Vol. 17, Dec. 1980, pp. 483-488.

8. Cohen, N. S. and Strand, L. O., "Effects of AP Size Distribution on the Pressure-Coupled Response Function," 18th JANNAF Combustion Meeting, CPIA Publication 347, Vol. III, Oct. 1981, pp. 7-20.

9. Flanigan, D. A. and Hessler, R. O., private communications, Thiokol Corporation, Huntsville, Ala., 1981.

10. Tien, J. S., "Oscillatory Burning of Solid Propellants Including Gas Phase Time Lag," J. Combustion Science and Technology, Vol. 5, 1972, pp. 47-54.

11. Cohen, N. S., "Workshop Report: HMX Propellant Combustion Modeling," 16th JANNAF Combustion meeting, CPIA Publication 308, Vol. III, Dec. 1979, pp. 219-240.

12. Lengelle, G., "Model Describing the Erosive Combustion and Velocity Response of Composite Propellants," AIAA Journal, Vol. 13, No. 3, March 1975, pp. 315-322.

13. King, M. K., "A Model of Erosive Burning of Composite Propellants," J. Spacecraft & Rockets, Vol. 15, No. 3, May-June 1978, pp. 139-146.

14. Condon, J. A. and Osborn, J. R., "The Effect of Oxidizer Particle Size Distribution on the Steady and Nonsteady Combustion of Composite Propellants," AFRPL-TR-78-17, Purdue University, W. Lafayette, Ind., June 1978.

15. Beddini, R. A., "Reacting Turbulent Boundary Layer Approach to Solid Propellant Erosive Burning," AIAA Journal, Vol. 16, No. 9, Sept. 1978, pp. 898-905.

16. Renie, J. P. and Osborn, J. R., "Erosive Burning," AIAA Paper 79-0165, 17th AIAA Aerospace Sciences Meeting, Jan. 1979.

17. King, M. K., "Erosive Burning of Composite Solid Propellants: Experimental and Modeling Studies," J. Spacecraft & Rockets, Vol. 16, No. 3, May-June 1979, pp. 154-162.

18. King, M. K., "A Model of the Effects of Pressure and Crossflow Velocity on Composite Propellant Burning Rate," AIAA Paper 79-1171, AIAA/SAE/ASME 15th Joint Propulsion Conference, June 1979.

19. Razdan, M. K. and Kuo, K. K., "Erosive Burning Study of Composite Solid Propellants by Turbulent Boundary-Layer Approach," AIAA Journal, Vol. 17, No. 11, Nov. 1979, pp. 1225-1233.

20. Renie, J. P. and Osborn, J. R., "Pressure and Velocity Coupled Response of Composite Solid Propellants Based Upon a Small Perturbation Analysis," AIAA Paper 81-1556, AIAA/SAE/ASME 17th Joint Propulsion Conference, July 1981.

21. Arora, R., Wu, X., White, F. X. and Kuo, K. K., "Erosive Burning of Composite Solid Propellants: Mechanisms, Correlation and Application to Grain Design," AIAA Paper 81-1581, ibid.

22. Brown, R. S., Willoughhy, P. G. and Waugh, R. C., "Coupling Between Velocity Oscillations and Solid Propellant Combustion," 1982 AFOSR/AFRPL Rocket Propulsion Research Meeting, Lancaster, Calif., March 1982.

23. Ben Reuven, M. and Summerfield, M., "Analysis of Combustion Oscillations in Heterogeneous Systems," PCRL-FR-82-004, Contract F49620-81-C-0018, Princeton Combustion Research Laboratory, Princeton, N. J., June 1982.

24. Flandro, G. A., "Nonlinear Time Dependent Combustion of a Solid Propellant Rocket," 19th JANNAF Combustion Meeting, CPIA publication pending.

25. Unpublished work in progress under Contract F04611-81-C-0007, "Nonlinear Stability for Tactical Motors," Aerojet Tactical Systems Co., Sacramento, Calif.

26. Levine, J. N. and Baum, J. D., "A Numerical Study of Nonlinear Instability Phenomena in Solid Rocket Motors," AIAA Paper 81-1524, AIAA/SAE/ASME 17th Joint Propulsion Conference, July 1981.

27. Saderholm, C. A., "A Characterization of Erosive Burning for Composite Propellants." presented at the AIAA Solid Propellant Rocket Conference, Palo Alto, Calif., Jan. 1964.

28. Hessler, R. D., private communications, Thiokol Corporation, Huntsville, Ala., 1981.

29. Mikkelsen, C. O. and Roys, G. P., "Application of the Saderholm Erosive Burning Model to Nozzleless Solid Propellant Rocket Motors," AIAA Paper 82-1146, AIAA/SAE/ASME 18th Joint Propulsion Conference, June 1982.

30. Razdan, M. K. and Kuo, K. K., "Turbulent Flow Analysis and Measurements of Erosive-Burning Rates of Composite Solid Propellants," AIAA Paper 80-1209, AIAA/SAE/ASME 16th Joint Propulsion Conference, June 1980.

31. Cohen, N. S. and Strand, L. D., "An Improved Model for the Combustion of AP Composite Propellants," AIAA Journal, Vol. 20, No. 12, Dec. 1982, pp. 1739-1746.

32. King, M. K., private communication, Atlantic Research Corporation, Alexandria, Va., 1982.

33. Oehority, G. L. and Price, E. W., "Axial Mode, Intermediate Frequency Combustion Instability in Solid Propellant Rockets," NWC-TP-5654, U.S. Naval Weapons Center, China Lake, Calif., Oct. 1974.

34. Kruse, R. B., Glick, R. L. and Cohen, N. S., "Velocity Coupled Instability in Prototype RS MK-36 Motors," 16th JANNAF Combustion Meeting, CPIA Publication 308, Vol. III, Dec. 1979, pp. 559-574.

35. Brownlee, W. G., "Nonlinear Axial Combustion Instability in Solid Propellant Rocket Motors," AIAA Journal, Vol. 2, No. 2, Feb. 1964, pp. 275-284.

36. Roberts, A. K. and Brownlee, W. G., "Nonlinear Longitudinal Combustion Instability: Influence of Propellant Composition," AIAA Journal, Vol. 9, No. 1, Jan. 1971, pp. 140-146.

37. Hughes, P. M. and Smith, D., L., "Nonlinear Combustion Instability in Solid Propellant Rocket Motors - Influence of Geometry and Propellant Formulation." 53rd Meeting of the Propulsion and Energetics Panel of AGARD, AGARD-CP-259 on Solid Rocket Motor Technology, Paper No. 26, April 1979.

38. Beckstead, M. W., "Model for Double-Base Propellant Combustion," AIAA Journal, Vol. 18, No. 8, Aug. 1980, pp. 980-985.

39. Cohen, N. S., "Analysis of Double-Base Propellant Combustion," AIAA Paper 81-0120, 19th AIAA Aerospace Sciences Meeting, Jan. 1981.

40. Oenison, M. R. and Baum, E., " A Simplified Model of Unstable Burning in Solid Propellants," ARS Journal, Vol. 31. No. 8, August 1961, pp. 1112-1122.

41. Kubota, N., et al., "The Mechanism of Super-Rate Burning of Catalyzed Double-Based Propellants," Fifteenth Symposium (International) on Combustion, Combustion Institute, Pittsburgh, Pa., 1975, pp. 529-537.

42. Lengelle, G., et al., "Combustion Mechanisms of Double-Base Solid Propellants," Seventeenth Symposium (International) on Combustion, Combustion Institute, Pittsburgh, Pa., 1979, pp. 1443-1451.

43. Ben Reuven, M. and Caveny, L. H., "Nitramine Flame Chemistry and Deflagration Interpreted in Terms of a Flame Model," AIAA Paper 79-1133, AIAA/SAE/ASME 15th Joint Propulsion Conference, June 1979.

44. Cohen, N. S., Lo, G. A. and Crowley, J. C., "Simplifications and Variations of the Ben Reuven-Caveny Model of HMX Combustion," 18th JANNAF Combustion Meeting, CPIA Publication 347, Vol. II, Oct. 1981, pp. 361-372.

## ABBREVIATIONS AND ACRONYMS

ABL     Allegany Ballistics Laboratory

AFRPL   Air Force Rocket Propulsion Laboratory

AIAA    American Institute of Aeronautics and Astronautics

AP      ammonium perchlorate

CARDE   Canadian Armament Design and Experimental Establishment

CPIA    Chemical Propulsion Information Agency

EDAX    energy dispersive analysis of x-rays

HTPB    hydroxy-terminated polybutadiene

JANNAF  Joint Army Navy NASA Air Force

SEM     scanning electron microscope

SRM     solid rocket motor